
**FIGURE 7. The University Network of Interactive Labs (UNILabs) web portal.**

An analysis of this plot helps with the system identification problem since it provides information about poles and zeros of the open and closed loop transfer functions of the system. The VL is also provided with an option to automatically obtain the Bode plot and the data array. Figure 2.f shows a simple Bode plot with fifty different frequencies. Increasing the number of frequencies of the sweep and saving the values, a student can process the data (stored in .m files) and obtain the plot of Figure 6, which shows a magnitude-frequency graph in open loop and in closed loop (for coupled and uncoupled control) in simulation mode.

This activity can be performed in both laboratories, but the range of frequencies is reduced for the remote version due to system limitations.

### *D. DISTURBANCES ANALYSIS*

The 2D visualization allows introducing an isolated perturbation, by clicking and dragging the pulley, to obtain the natural frequency and damping ratio of the system. This can be used for studying the double complex pole of the system in order to identify the transfer function in the virtual laboratory (in remote version is not yet available).

### *E. USER DEFINED CONTROLLER*

As an advanced task, the user can write different controllers to use in the control loop. This tool extend the use of the laboratory either for investigation or learning purposes. The code of the controller can be written in Java or Javascript syntax and the *Auxiliar Variables* graph allows analyzing the controller outputs. By using this option the students can:

- Add features to the basic web-lab built-in PID controller.
- Analyze and compare the behavior of well-known controllers for learning purposes.
- Develop/test a controller for investigation purposes.

At the moment of writing these lines, this activity is only possible with the virtual laboratory. In the remote version, this option is disabled for preventing possible damages in the belt and the pulley.

## IV. UNILABS

In a control engineering and scientific context, UNILabs (successor of the UNEDLabs [39] and the AutomatL@bs [30] projects), constitutes a network of web-based laboratories in which several Spanish universities take part. UNILabs web portal is based on Moodle and all the available VRLs are developed using EJS. This initiative of sharing resources increases the number of available experimental setups for both students and instructors. The network hosts 15 virtual and remote laboratories (i.e. 30 web-labs, either simulations or remotely-operated experiments) from 8 different universities. This work presents the first open course in

UNILabs, which offers several VRLs freely accessible thanks to the low-cost solution proposed here.

The web portal provides a social context for students' collaboration. Moodle enriches virtual and remote labs by facilitating and promoting the tools for students to discuss the experiments between them and teachers, exchange their lab reports, work in collaborative sessions [40], etc. In addition, Moodle helps to distribute all the convenient resources for a complete online experiment. For instance, attached to the web-lab, a course in Moodle may include a description of the phenomena under study, videos, the tasks protocol students must follow, a questionnaire, etc. Finally, Moodle allows creating open courses that are accessible and available for anyone. This allows our labs, both the virtual and remote ones, to be usable for any person who might be interested (i.e. students who want to learn more on their own, or teachers who want to use them for demonstration purposes in their classes).

Figure 7 contains the main view of UNILabs web portal. Accessing the open course in UNILabs, it offers three modules or didactical units up to date, all of them on the automatic control field:

- *The heat-flow system* - Experimenting with transfer delay effects in a second order plant.
- *The DC motor system* - Position and speed control in a first order plant with rapid dynamics.
- *The coupled electric drives system* - Presented in this paper and used for MIMO control.

More information about these labs can be found in the open course of UNILabs.

## V. CONCLUSIONS

While VLs and simulations are common on the Internet and can be often used and/or downloaded for free, open RLs, however, are very rare to find. This is due to two facts: 1) they are more expensive to create and maintain and 2) the maintenance to ensure the correct operation of a RL requires time and attention. The solution provided in this work partially solves the first problem (since it is based in a low-cost card, the BeagleBone Black board, and the use of a free tool called EJS for building the lab interface), and also helps with the second one (since the integration of the RLs into a free LMS, Moodle, provides management and maintenance facilities in a software level).

The development of new virtual and remote laboratories is important to increase the subjects covered in UNILabs. A new virtual and remote laboratory to carry out control practices in a $2\times2$ MIMO system with industrial applications is now available in the University Network of Interactive Laboratories Moodle web portal. The virtual and the remote labs are accessible for anyone in a new open course, providing activities to experiment with different control concepts such as PID tuning, frequency response and disturbance analysis.

This open course also offers two additional VRLs: one of a DC motor and another of a heat-flow system. All the RLs in this course have been developed using the low-cost approach described in this work, that replaces the PC used in previous laboratories with a cheaper DAQ system.

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**JACOBO SÁENZ** received the M.Sc. degree in physics from the Complutense University of Madrid, Spain, in 2013. He is currently pursuing the Ph.D. degree with the Department of Computer Sciences Automatic and Control, National University of Distance Education, Madrid. His research interests include virtual and remote laboratories, control engineering, and heuristic algorithms.

**JESÚS CHACÓN** received the M.Sc. degree in automation and industrial electronics engineering from the University of Córdoba, Spain, in 2010, and the Ph.D. degree in computer science from the National University of Distance Education (UNED), Madrid, Spain, in 2014. Since 2010, he has been with the Department of Computer Sciences and Automatic Control, UNED, as a full-time Researcher. His current research interests include simulation and control of event-based control systems, and remote and virtual laboratories in control engineering.

**LUIS DE LA TORRE** received the M.Sc. degree in physics from the Complutense University of Madrid, Spain, in 2008, and the Ph.D. degree in systems engineering and automatic control from the National University of Distance Education (UNED), Madrid, in 2013. He is currently an Assistant Professor with the Department of Computer Sciences Automatic and Control, UNED. His research interests include virtual and remote laboratories, distance education, evolutionary algorithms, UAV (Unmanned Aircraft Vehicle)s, and path planning.

**ANTONIO VISIOLI** (SM'07) was born in 1970. He received the Laurea degree in electronics engineering from the University of Parma, Parma, Italy, and the Ph.D. degree in applied mechanics from the University of Brescia, Brescia, Italy, in 1995 and 1999, respectively. He is currently an Associate Professor of Automatic Control with the Department of Mechanical and Industrial Engineering, University of Brescia. He has edited one book, and authored or co-authored two monographs, one textbook, and about 200 papers in international journals and conference proceedings. His research interests include industrial robot control and trajectory planning, process control, and fractional control. He is a member of the IFAC and a Board Member of the Italian Association for the Automation. He serves as a member of the Technical Committee on Control Education of the IEEE Control Systems Society and the IFAC Technical Committee on 9.4 Control Education.

**SEBASTIÁN DORMIDO** received the B.S. degree in physics from Complutense University, Madrid, Spain, in 1968, the Ph.D. degree in the sciences from Basque Country University, Bilbao, Spain, in 1971, and the Doctor Honorary degree from the Universidad de Huelva and the Universidad de Almería. In 1981, he was appointed as a Professor of Control Engineering with the National University of Distance Education, Madrid. He has authored or co-authored over 250 technical papers in international journals and conferences, and has supervised over 35 Ph.D. theses. His scientific activities include computer control of industrial processes, model-based predictive control, hybrid control, and Web-based laboratories for distance education. From 2001 to 2006, he was the President of the Spanish Association of Automatic Control, CEA-IFAC. He has received the National Automatic Control Prize from the IFAC Spanish Automatic Control Committee.